Simulating solar cells with PC1D

World Record Si Cell

- Very recent (announced a few days ago) results from Longi Solar → **27.81%**
  - V_{OC} = 744.9 mV
  - FF = 87.55%
  - J_{SC} = 42.64 mA/cm^2
- Longi leading perovskite-Si tandem efficiency race with **34.6%** (1 cm^2) and **31%** (wafer-scale – M6)
- What about EPFL-CSEM? → 25.4% Si record 25 cm^2
  31.6% perovskite-Si 1 cm^2
  28.9% perovskite-Si 60 cm^2

Today's Challenge → to simulate higher performance than 27.8%

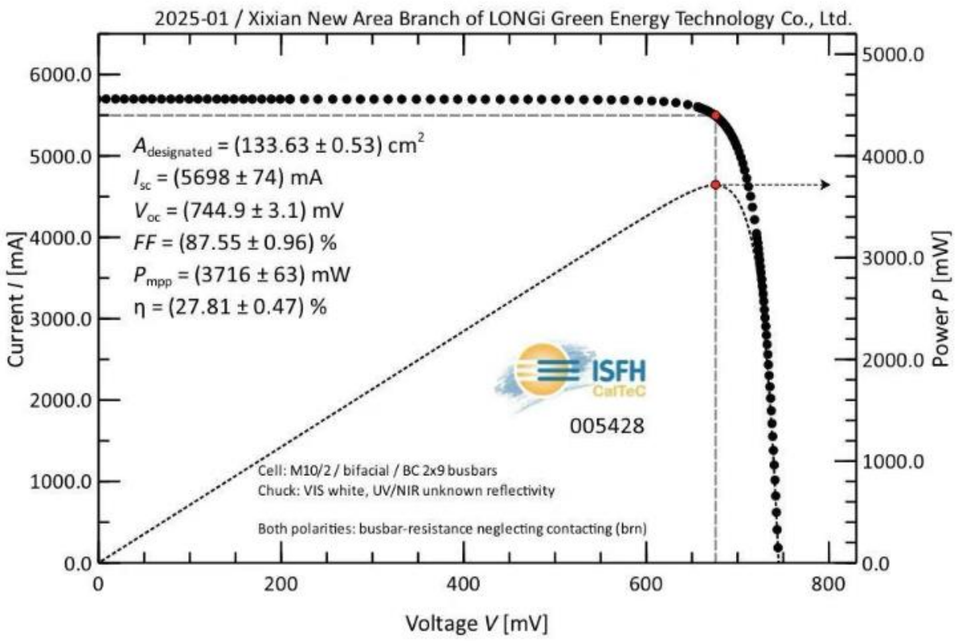
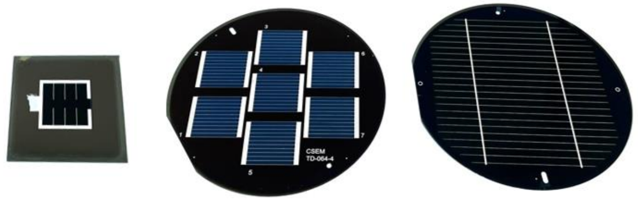
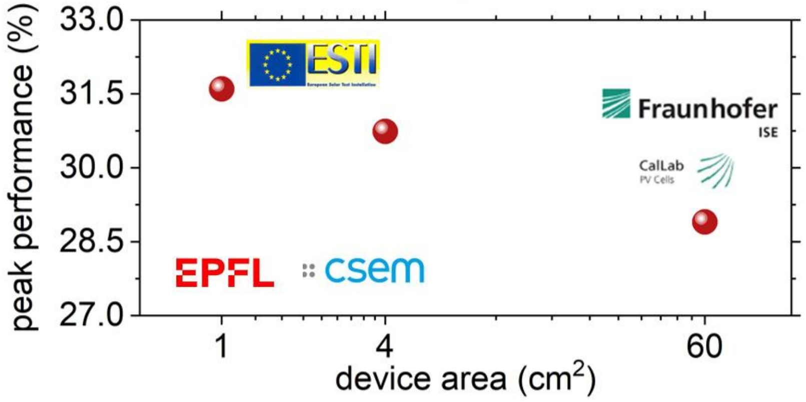


Fig. 2: Plot of the measured current-voltage characteristics under standard test conditions.

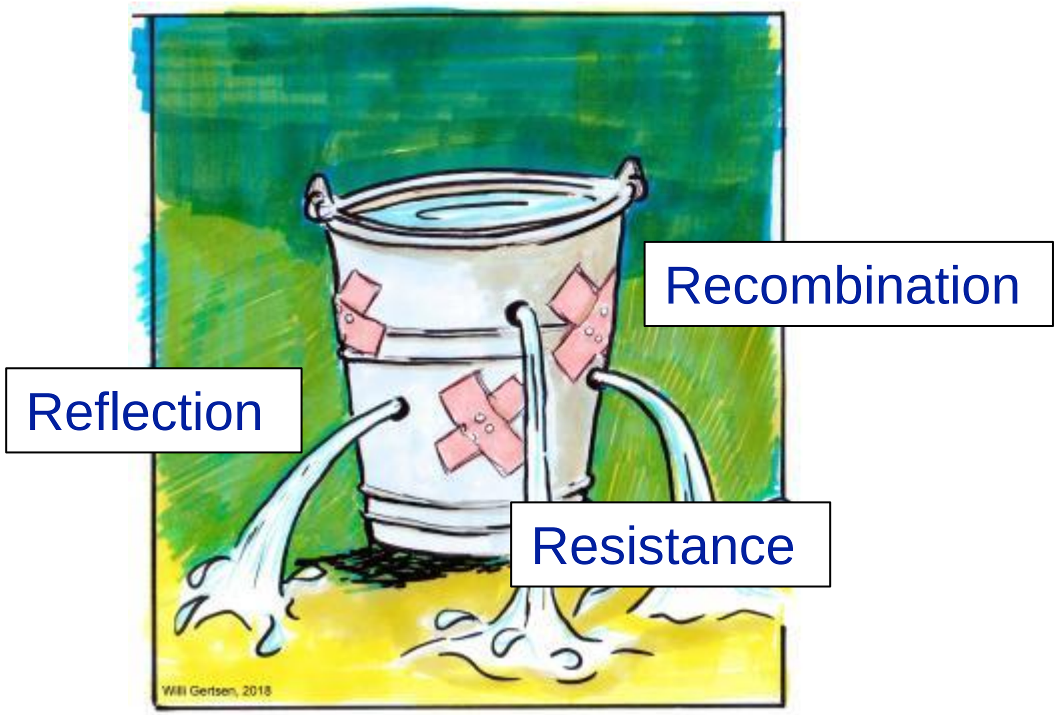




Simulating solar cells - Why?

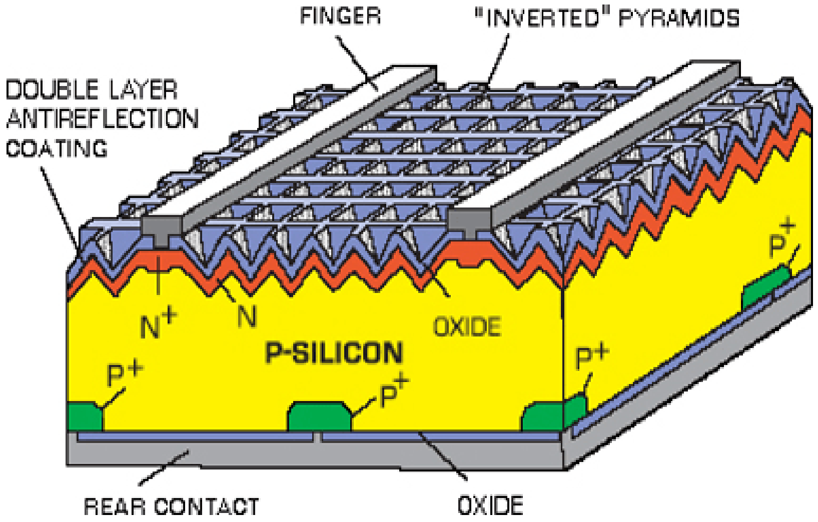
- Analytical solutions to solar cell equations are not always possible.
- Performance of various parts of the cell can have a synergetic effect on the result → the Bucket analogy.
- Simulations are beneficial for
  - Better understanding of loss channels
  - Estimating gains
  - Maximizing performance

Cell efficiency = How full the bucket is

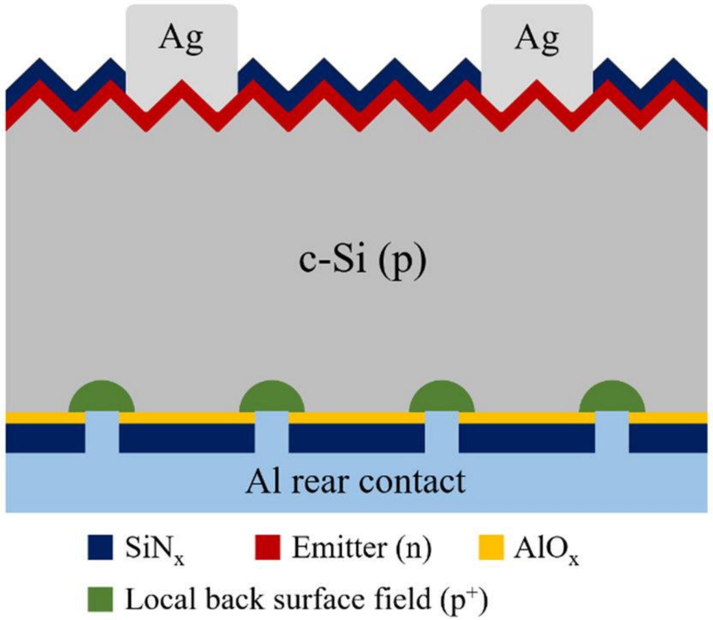


Simulation of solar cells - Complex to simple

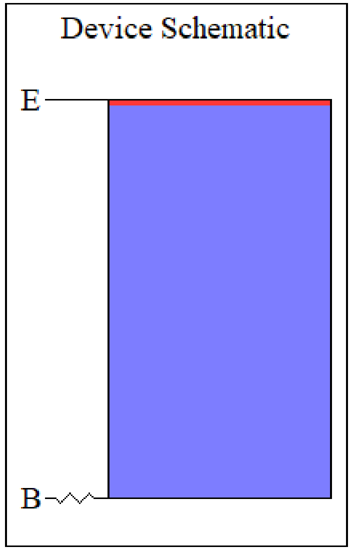
3D



2D



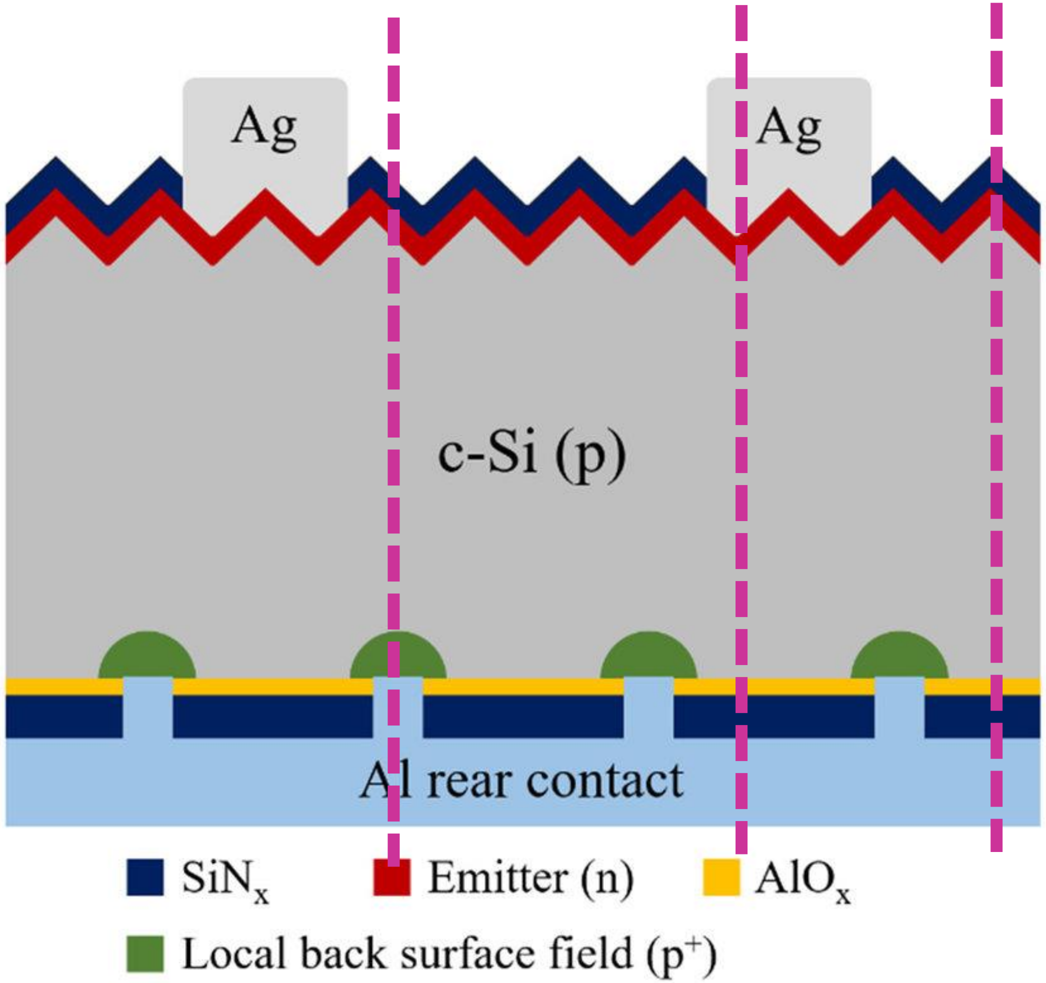
1D

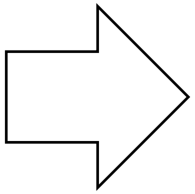


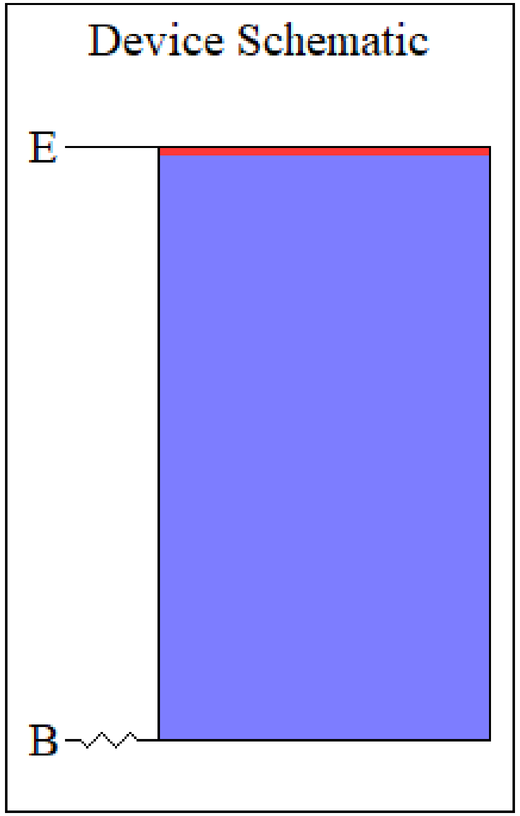
Emitter (p)

Base (n)

Transformation to 1D







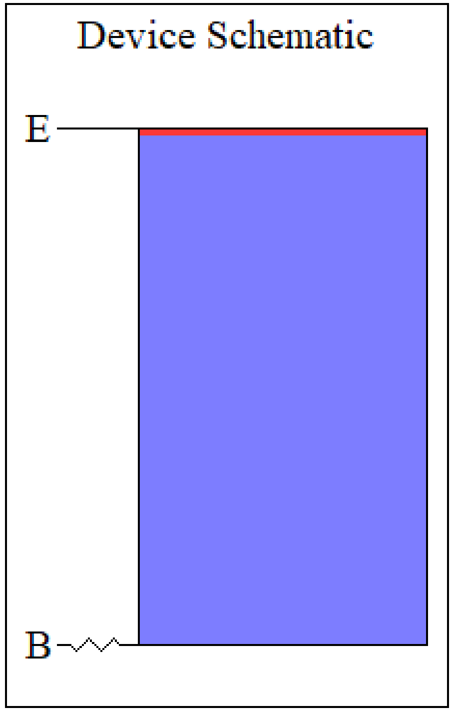
PC1D - 1D numerical solver for solar cells

- Solves the following equations numerically.

Poisson's equation ⇨ $$\frac{d\mathbf{E}}{dx} = \frac{\rho}{\varepsilon} = \frac{q}{\varepsilon}(p(x) - n(x) - N_A^- + N_D^+)$$

Drift-diffusion ⇨ $$J_n = q\mu_n n\boldsymbol{E} + qD_n\frac{dn}{dx}\ , \quad J_p = q\mu_p p\boldsymbol{E} + qD_p\frac{dp}{dx}$$

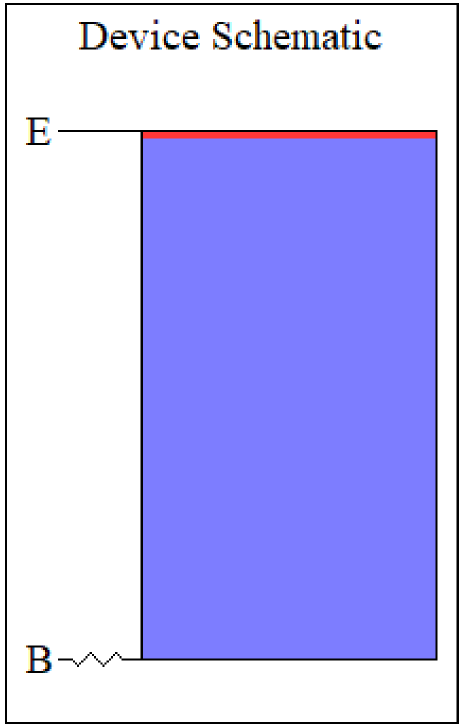
Continuity (at steady-state) ⇨ $$\frac{1}{q}\frac{dJ_n}{dx} = U - G$$ $$\frac{1}{q}\frac{dJ_p}{dx} = -(U - G)$$



Today

- Download the PC1D application files from Moodle.

- Start from a bad performing cell and improve the performance step by step in terms of
  - Electronics
  - Optics



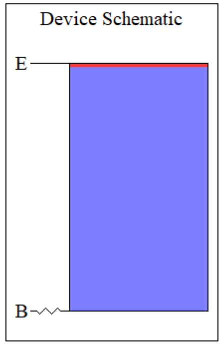
PC1D - Interface

- You can modify various input parameters by clicking on them with your cursor.
- Results at the bottom and in the 4 section panel.

DEVICE
Device area: 100 cm^2
No surface texturing
No surface charge
Front surface optically coated
No Exterior Rear Reflectance
Internal optical reflectance enabled
Rear surface optically rough
Emitter contact enabled
Base contact: 0.01 Ω
No internal shunt elements

REGION 1
Thickness: 180 µm
Material modified from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.abs
Free carrier absorption enabled
P-type background doping: 1.513×10^{16} cm^{-3}
1st front diff.: N-type, 1×10^{20} cm^{-3} peak
No 2nd front diffusion
No rear diffusion
Bulk recombination: $\tau_n = \tau_p = 30$ µs
Front-surface recom.: S model, $S_n = S_p = 10000$ cm/s
Rear-surface recom.: S model, $S_n = S_p = 1000$ cm/s

EXCITATION
Excitation from one-sun.exc
Excitation mode: Transient, 32 timesteps
Temperature: 25°C
Base circuit: Sweep from -0.8 to 0.8 V
Collector circuit: Zero
Primary light source enabled
Constant intensity: 0.1 W cm^{-2}
Spectrum from am15g.spc
Secondary light source disabled

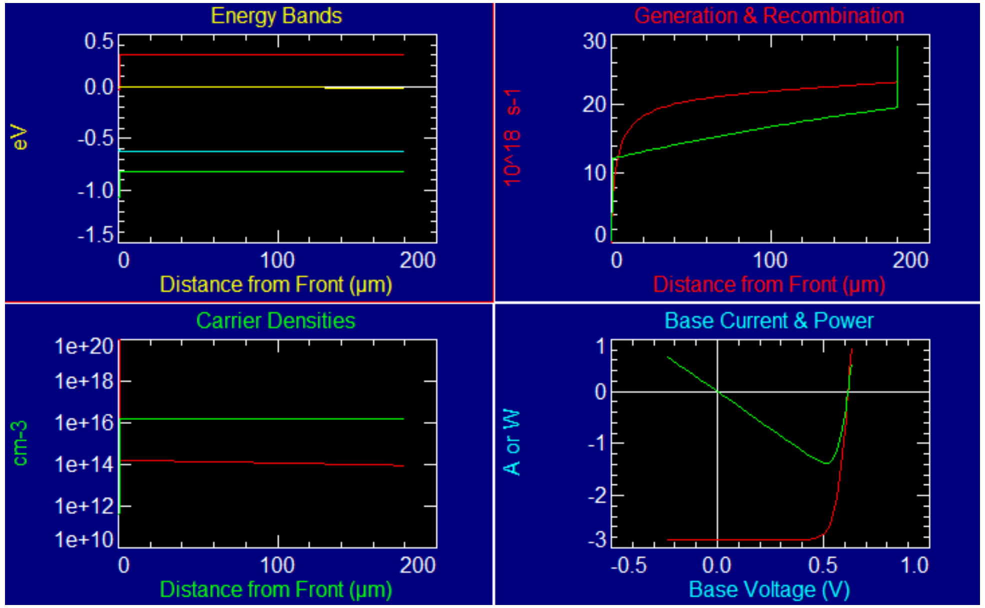


RESULTS
Short-circuit Ib: -2.839 amps
Max base power out: 1.378 watts
Open-circuit Vb: 0.6151 volts

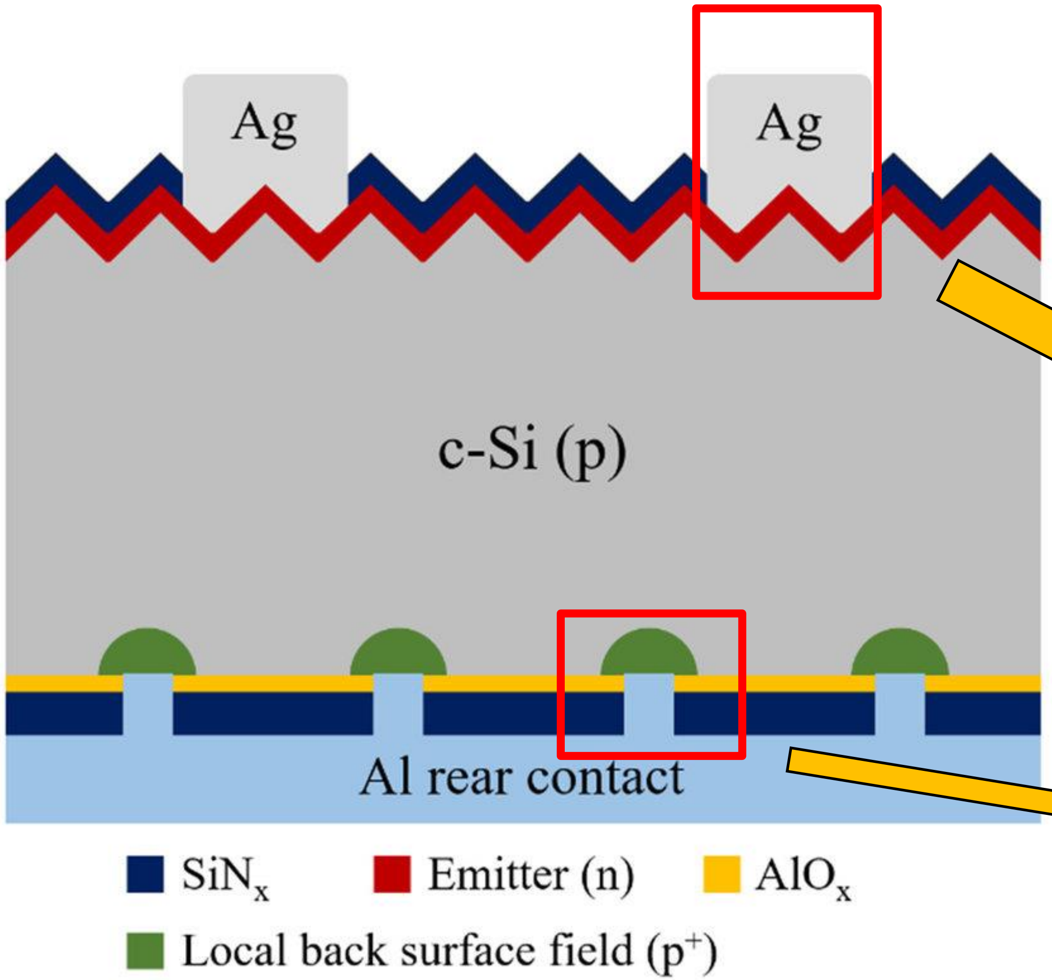
Input power = 1000 W/m^2
→ 10 W for 100 cm^2

Efficiency = 1.378/10 = **13.78%**

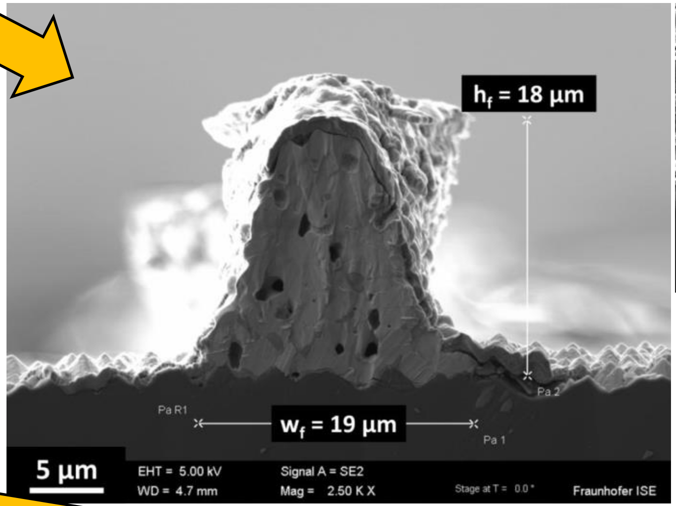
Current density = 2.839 / 100 cm^2
= 28.39 mA/cm^2

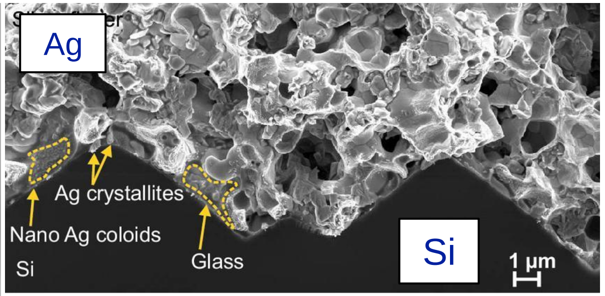


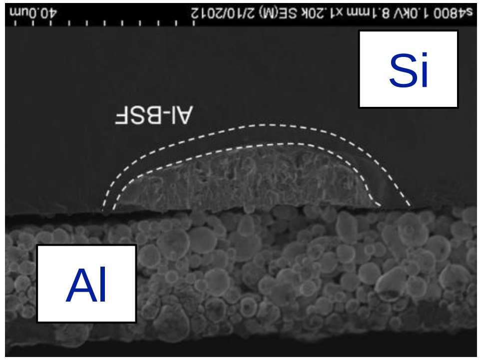
Ex. 1 – Surface recombination



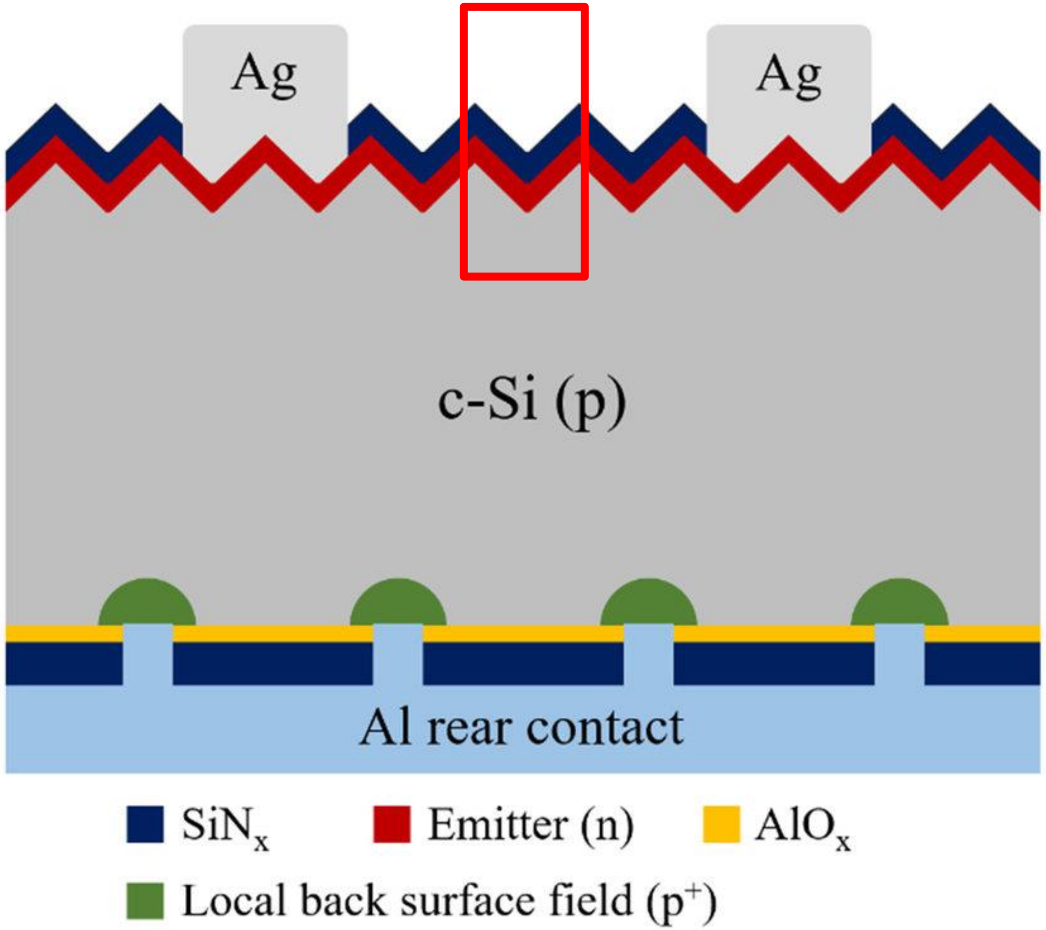
- At the direct metal-Si contact → 1e7 cm/s
  - The upper limit for velocity
  - Carriers cannot move faster than this in the absorber





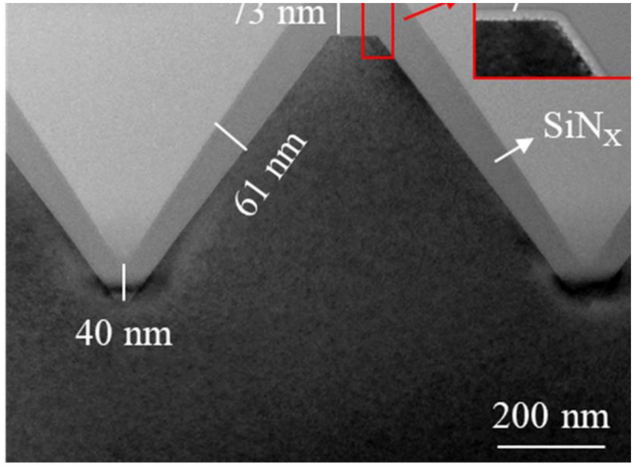


Ex. 1 – Surface recombination

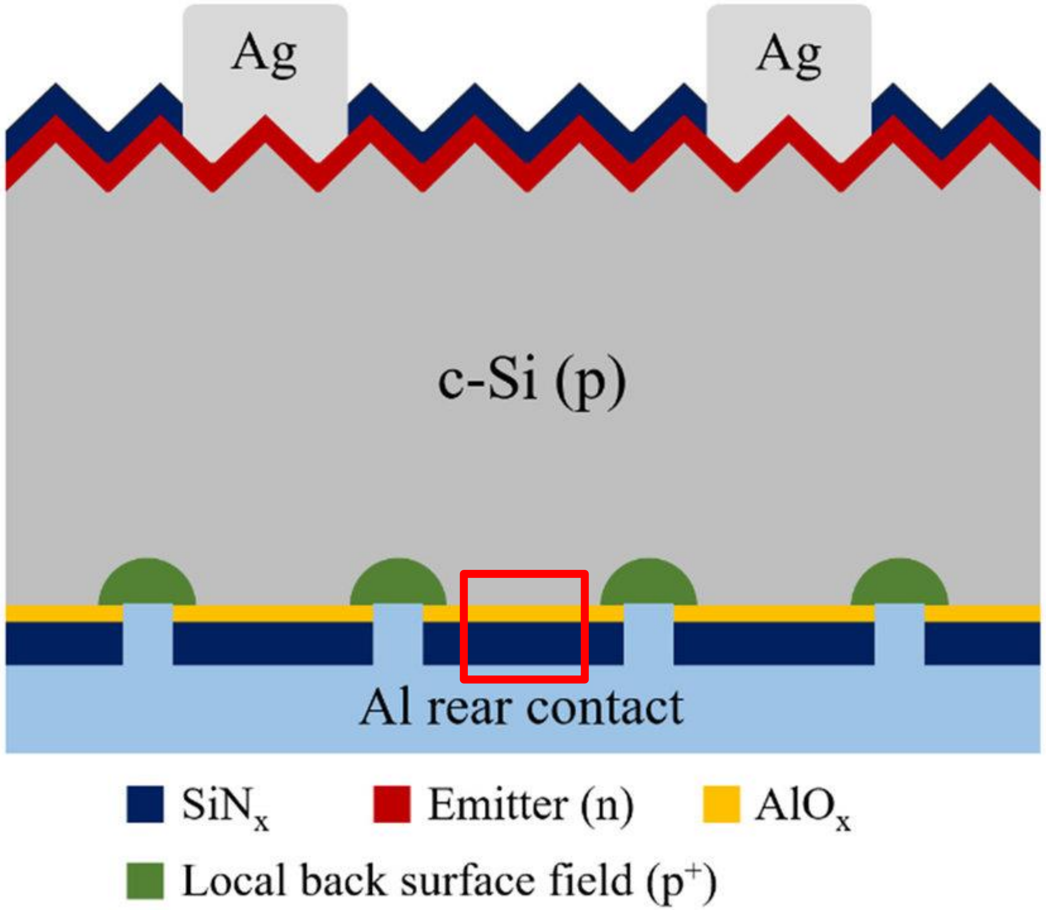


- At the direct metal-Si contact → 1e7 cm/s
  - The upper limit for velocity
  - Carriers cannot move faster than this in the absorber

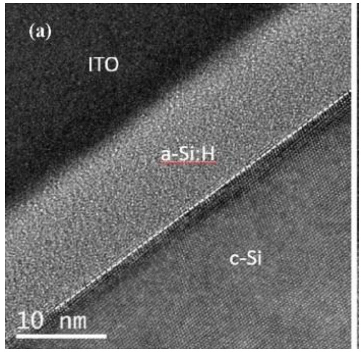
- Surface of a highly doped region (e.g. emitter) → **Typically higher than 1e3 cm/s**
  - Depends on doping density



Ex. 1 – Surface recombination

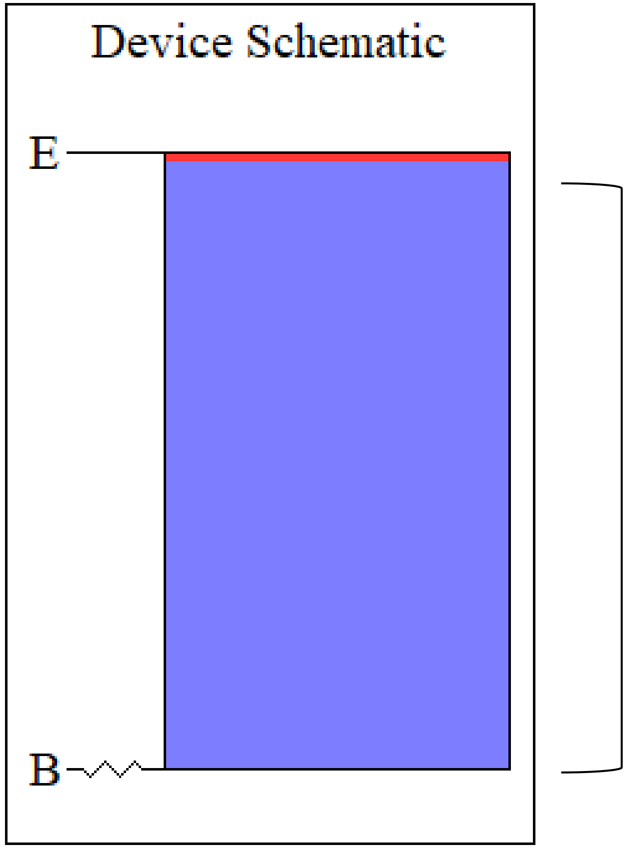


- At the direct metal-Si contact → 1e7 cm/s
  - The upper limit for velocity
  - Carriers cannot move faster than this in the absorber
- Surface of a highly doped region (e.g. emitter) → Typically higher than 1e3 cm/s
  - Depends on doping density
- Lowly doped c-Si wafer passivated with a dielectric (e.g. AlOx) or amorphous Si → **Less than 10 cm/s.**



Ex. 2 – Bulk lifetime

- Bulk (wafer) thicknesses → Typically 100-300 um.
- Lifetime → Function of doping density (or resistivity).
- State of the art lifetimes for commonly used bulk dopings (e.g., 1e15 to 16 cm-3) **> 5 ms.**
  - At low injection

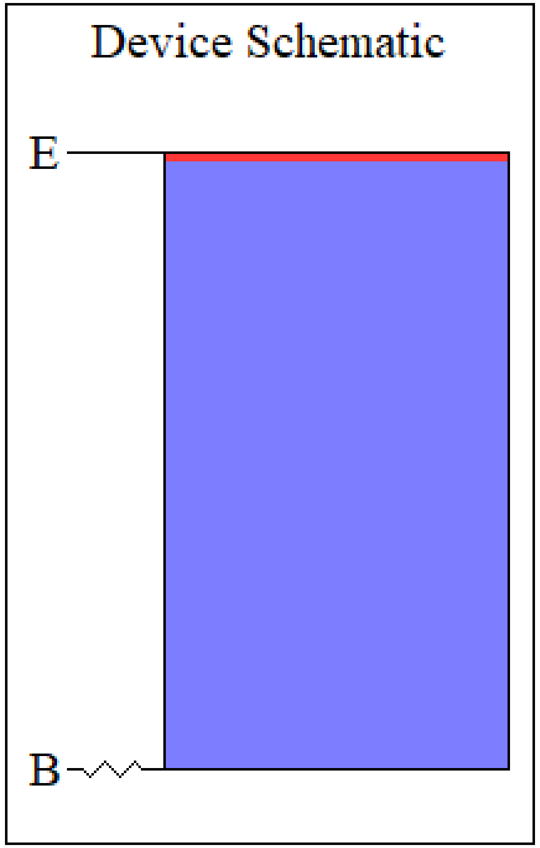


Bulk = blue part

Ex. 2 and 3 – Emitter

- Highly doped, much thinner than base.
  - Typically shorter than 1 um.

- Losses:
  - Auger recombination
    - Increases with doping and thickness
  - Carrier collection
    - Harder to collect with increased doping and thickness because of the reduced diffusion length.

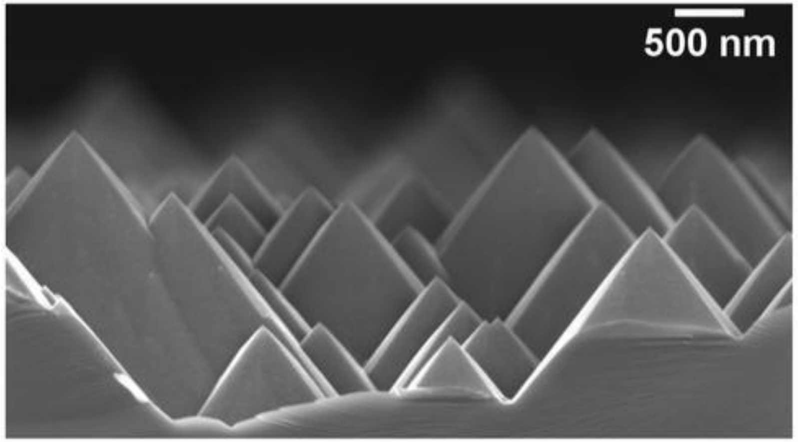


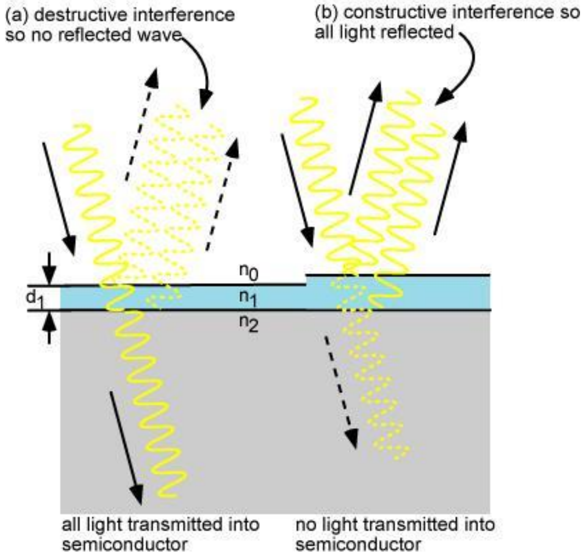
Emitter = red part

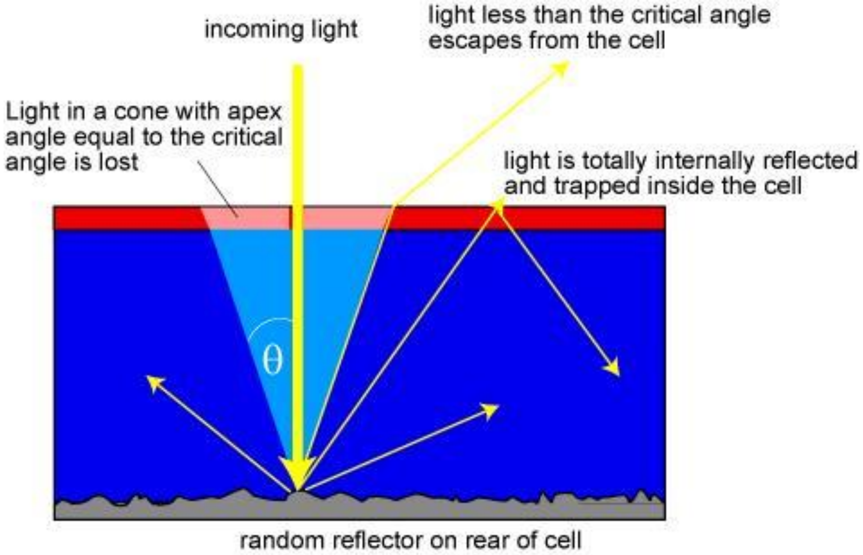
Ex. 4 – Optics

- Improved by
  - Anti-reflection coating
  - Texturing
  - IR reflector, scatterer at rear

Reduced front reflectance







Ex. 5 – The perfect cell

- What are the remaining losses?
- How high you can go in efficiency?
- Try and see for yourself ☺

World Record Si Cell

- Very recent (announced a few days ago) results from Longi Solar → **27.8%**
  - V_{OC} = 744.9 mV
  - FF = 87.55%
  - J_{SC} = 42.64 mA/cm^2

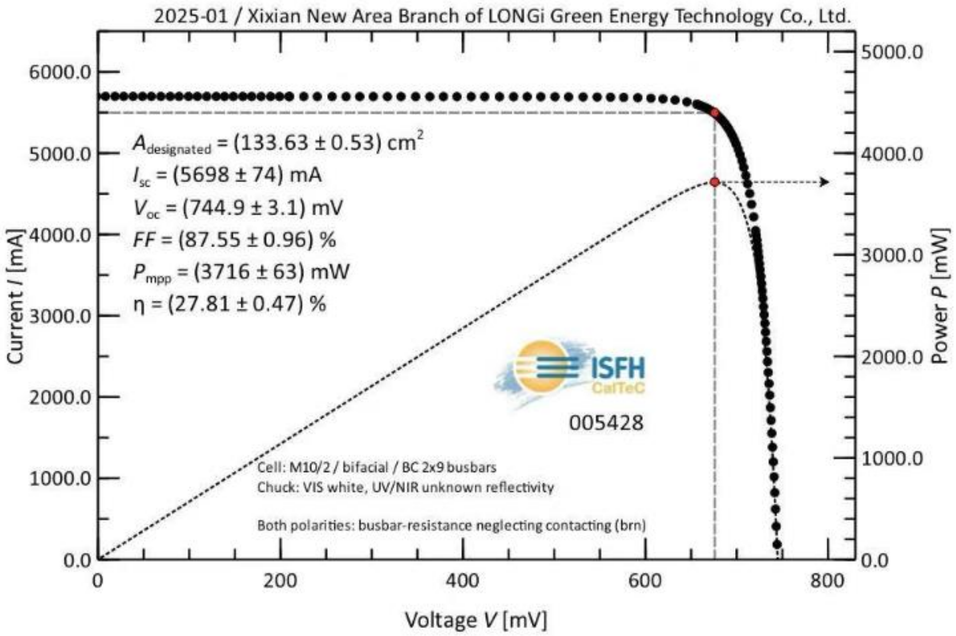


Fig. 2: Plot of the measured current-voltage characteristics under standard test conditions.